Testing smarter control and feedback with users: time, temperature and space in household heating preferences and practices in a Living Laboratory

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Abstract: Transitioning to more efficient and less carbon-intensive heating is a monumental policy challenge in the United Kingdom. However, very few households in the UK—and perhaps even elsewhere—have actual experience with state-of-the-art smart heating systems that may utilize enhanced control or feedback. Drawing from a unique sample of actual adopters of smart heating, this study closely examines the heating preferences, practices, and profiles of homes when they are given smarter heating systems. The study utilizes qualitative household data from the Energy System Catapult's Living Laboratory of 100 smart homes in Birmingham (West Midlands), Bridgend (Wales), Manchester (Greater Manchester), and Newcastle (Northumberland). We examine the heating preferences and profiles of participants, with findings inductively organized around the themes of temperature, including tradeoffs between comfort, cost, and value; time, including the utility of heat scheduling; and space, including zonal heating controls. We also discuss patterns of learning, the emergence of environmental values, and issues of discomfort. We conclude by commenting on important distinctions between radiant and ambient heat, as well as between scheduled and on-demand heat. The main findings are 1) tradeoffs between comfort, value and cost occur when it comes to smart heating; 2) people want different numbers of warm hours in their homes at very different times; 3) households chose to heat different numbers of rooms; and 4) there are other non-monetary and non-functional aspects of smart heating that households value.

Keywords: smart energy; heating and cooling; living lab; energy practices; smart homes; big data; energy feedback

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1. Introduction

One of the stickiest or most difficult sectors, to decarbonize is heating and cooling. Heat consumption is often shaped by both structural and human aspects, by the existing long-lived infrastructures, such as physical heat networks, and social practices, both of which are resistant to change (Hansen 2018; Hansen 2016). In the United Kingdom (UK), space heating accounts for approximately two thirds of average total energy use in homes, and hot water a further 15% (Palmer and Cooper 2013; BEIS 2016). This means residential heating accounts for about 20% of total carbon emissions in the UK (ETI 2015). The UK spent about £5 billion on heat in 1970, but the amount increased by 27-fold in 2011, totaling £134 billion that year (Abu-Bakar et al. 2013). The cumulative cost of decarbonizing the UK heat system could be as much as £450 billion (NIC 2018).

Yet heat is also a sector, or energy service, that is prone to severe inefficiencies and waste. For instance, one older survey of 21,900 homes in England noted that 98% had a gas boiler for central heating (so no heat pumps or district heating) and that these had only simple controls such as an on/off switch or a timer (Munton et al. 2014). Similar evidence from the government suggested that of the 95% of all UK homes that have a gas boiler, 800,000 have no controls at all, and almost 8 million have no room thermostats (Department of Energy and

Climate Change 2012). The use of gas boilers in the UK is slow to change: 2019 was a "record year" for gas boiler sales in the UK, which grew by 1.8% and surpassed 1.67 million, with the number of homes with gas central heating rising to a historic high at 22 million homes (Installer Magazine 2020).

An estimated 60% of gas-connected homes in the UK have higher efficiency condensing boilers (Climate Change Committee 2016), but without adequate controls these may not be used in the most efficient way. Furthermore, heating density plots show that many people leave their heating on all the time, from morning to night. Very few homes in the UK have low-carbon heating. Using a different dataset, the Department for Business, Energy & Industrial Strategy (BEIS) (2018) estimates that 85% have gas central heating, 4% oil central heating, 5% electric storage heaters, 2% heat networks and most of the remaining 4% rely on electric room or central heating. Gas central heating is preferred by 90% of homes if they are given the choice (DECC 2013).

Much of the debate concerning the move towards low-carbon heating remains conceptual rather than empirical, given that very few households in the UK (and elsewhere) have actual experience with state-of-the-art low-carbon heating systems. It is an area with few early adopters, especially in a regime such as the UK known for its infrastructure, and subsequent preference, for gas boilers. We address this critical gap by drawing on original data from 100 homes in the UK that have trialed smart heating controls over the course of three years. Even though the 100 homes do not necessarily employ low-carbon heating sources *per se*, the use of smart heating systems have been recognized as a key part towards reducing heating demand and decarbonizing the UK's heating sector (BEIS 2018). Previous work emerging from this particular Living Laboratory has explored the range of heating needs demanded by households during the trial phase (Mallaband and Lipson 2020) and active conflicts over heating activities, settings, or values over the course of a heating season (Sovacool et al. 2020). However, no studies have yet described the overall heating preferences and practices of participants, or examined closely the tensions and tradeoffs in heating profiles.

We ask in this study: what are the heating preferences, practices, and profiles of homes when they are given smarter heating systems as well as enhanced control? We present a rich set of novel and original empirical qualitative household data drawn from the first and longest running "Living Laboratory" in the UK, a quasi-experimental research project involving three years of real-world operating data from 100 homes across four cities of Birmingham, Manchester, Newcastle, and Bridgend. Based on these data, we examine the heating preferences and profiles of participants, with findings inductively organized around the themes of *temperature* (including tradeoffs between comfort, cost, and value); *time* (including preferences for scheduling compared with ad hoc overrides); and *space* (including zonal heating controls). We also discuss patterns of learning, the emergence of environmental values, and issues of discomfort. We conclude with an array of policy findings and insights for system designers, retailers and policymakers. Our study in particular can provide a rich enough understanding of what consumers want from their heating to assist those attempting to manage demand or design innovations (such as heat pumps) around household needs (Eggimann et al. 2019).

2. Literature review: Previous research on smart controls and heating practices in the UK

For several years, research has tried to address the puzzle of energy practices and preferences—how energy is used in the home, by whom, to what extent and how its use could be influenced or shaped to be more sustainable (see for example Darby 2006, 2018; Dimitrokali et al. 2015; Gans et al. 2013; Kleiminger et al. 2014). Many previous studies agree that heating practices and patterns vary considerably, and are influenced by issues ranging from dwelling conditions to the age (Barnicoat and Danson 2015) and employment status of occupants (Kane et al. 2015), their family structures and wider lifestyle choices (Eon et al. 2017).

Previous research has for example reported the different ways in which room temperatures and household behaviors have been measured and monitored to gauge heating practices (e.g. Beizaee et al. 2015; Kane et al. 2015), including also the use of smart technologies for predicting when homes are being occupied (Kleiminger et al. 2014). The variety in occupancy rates has also been studied in relation to whether people match time spent at home with their heating usage. For example, an Australian study which monitored ten households by Eon et al. (2015) found variation in heating practices according to family size and employment status, with higher levels of heating linked to the amount of time people spent at home (those working out of the home heated their homes only in the mornings and evenings, whilst stay-at-home parents with kids used their heating all day). To the contrary, in a UK-based study with 50 participants, Miu et al. (2019) found that despite participants having fairly regular occupancy patterns, they did not in fact match their heating controls to their routines but left the heating on even when they were not at home.

The notion of flexibility in energy service practice has been highlighted for those energy services that use electricity (e.g. cooking, washing) (Powells et al. 2014), but when it comes to heating practice, this may be more rigid due to the seasonality of heating demand (on the future of electric heating in the UK, see also Darby 2018 as well as Lows et al. 2020). Dimitrokali et al. (2015) undertook a study of 86 occupants in the UK who were given smart heating controls (a thermostat, mobile app and an online portal) and found a mixed response to the trial. On one hand, participants stated that they liked the remote control option of their heating system and perceived it to have changed their behavior, yet in practice they mainly controlled their heating manually via thermostats (Dimitrokali et al. 2015). The perception of heating controls can thus seem to be different from people's actual practice, whether due to reasons of established habits (Dimitrokali et al. 2015) or the inflexibility of demand at peak heating times or seasons (Powells et al. 2014).

Heating practices are not only influenced by those more tangible issues like occupancy levels and time spent at home, but also by the more prosaic sphere of values and meanings that underpin how households use heating to achieve comfortable temperatures at home (Gram-Hanssen 2010). These, too, vary and are dynamic. Hards (2013), for example found that heating practices were linked to status, as well as stigma, with wealthier people being able to "do more" with heating such as install energy efficient or renewable technology. Kuijer and Watson (2017) have noted how heating practices in the UK are indeed intertwined with social norms which can include for example rules about how rooms are used, such as separate rooms for separate functions, leading to implications to both home design and space heating demand. Goodhew et al. (2017) write about how heating itself is full of misperceptions and mental models that do not actually reflect sustainable heating options, or somewhat baffling conceptions of how heat flows in a home, or how a thermostat works. Royston (2014) adds that people develop very personal ways of managing heat in the home, including interactions with different practices and technologies that help them not only generate heat, but to move it around or even prevent its movement around.

Part of the complexity with heat is that households often want to achieve multiple goals with heat, many of which conflict (Royston 2014). Goals such as thermal comfort or maintaining the right temperature for another person, pet, or material object, are not always aligned with those of saving money or mitigating climate change (Royston 2014). For example, Devine-Wright and colleagues found that older people in the UK particularly liked the lighting and glow from a heat source such as a fireplace, and even replicated this with low-carbon heating options (Devine-Wright et al. 2014). There can also be stark differences what is considered comfortable by different people occupying the same heated spaces (e.g. Sovacool et al. 2020).

Another part of the complexity is that heating needs can be adaptive, and change over time and space. Kuijer and Watson (2017) add that heating needs can be about securing *adaptive* thermal comfort, as thermal preferences change over time. Their work has shown for example how heating needs, and uses in the home, are not fixed and cannot be known in advance, but instead change as new heating technologies or services are introduced, and then domesticated into daily life and practice.

Some argue that this messiness of heating practices, preferences and control technologies requires energy literacy, and increasingly also digital literacy with the use of smarter heating controls. Barnicoat and Danson (2015) for example found in a study conducted with 19 older households in Scotland (ages 50-92) that participants had little knowledge of energy efficiency or smart control technology, also adding that their findings supported other similar studies. Collectively, this variety in heating patterns and the complexities of values and meanings influencing them, make heat practices difficult to change and steer towards sustainability (Eyre and Baruah 2015; Wade et al. 2016; Energy Systems Catapult 2019; Gross and Hanna 2019). It could also exlain why the last major transition to household heating in the UK—the transition from town gas to national gas in the 1960s and 1970s—required monumental efforts on behalf of the government and private sector and was implemented in a top-down, manner (Sovacool and Martiskainen 2020).

By examining heating practices and preferences in 100 homes in the UK, we add to this previously conducted research, which has shown that heating practice is an intimately and profoundly social process that coevolves with experiences, knowledge, and time, not just a technically or economically one, or a static one.

3. Research methods: The Energy Systems Catapult "Living Laboratory"

This section describes our research methods, including data collection and analysis, as well as limitations.

3.1 Conceptualizing a Living Lab

The central research design for this study is a fully operational Living Laboratory, with more details offered in Sovacool et al. (2020) as well as Energy Systems Catapult (2019a; 2019b). A Living Laboratory refers to a user-centered sort of social experiment with the objective of testing a novel technology or intervention in a real-world and real-time environment (Korsnes et al. 2018; Voytenko et al. 2016; JPI Urban Europe 2013: 3). Claude et al. (2017) note that Living Laboratories have emerged as a useful research design for helping treat potential adopters or consumers as active agents in the creation or innovation process, rather than merely passive consumers. Canzler et al. (2017) add that Living Laboratories enable "experimentation" spaces where inventions can be co-created, tested, and even validated by possible users. Living Laboratories have also become an essential feature in various literatures discussing "transition experiments " as well as "sustainability experiments" (Luederitz et al. 2017; Kivimaa et al. 2017; Korsnes et al. 2018; Sengers et al. 2019).

3.2 The Energy Systems Catapult Living Lab

Our study is based on a subset of qualitative household data from the Energy Systems Catapult (ESC) Living Laboratory in the United Kingdom (Energy Systems Catapult 2019). This Living Lab started with 30 homes in the Winter of 2016 as a pilot, before moving into 100 homes in 2017 and thereafter running into the current year of 2019-2020 (although this study only presents the results of data from the 2017 to 2018 phases). The ESC's Living Lab is the first and only one currently operating in the entire UK with a focus on energy. Participants were selected to reflect a range of household compositions and property types. They were recruited by telephone in four locations—Birmingham (West Midlands), Bridgend (Wales), Manchester (Greater Manchester), and Newcastle (Northumberland). All had to have a gas boiler, reliable Wi-Fi and a gas meter that could be read (i.e. not smart or pre-pay) for the system to work. All participants owned their home (so they could take decisions about installing the hardware) and a smart phone or tablet (so they could interact with the system). Recruitment screened out anyone planning to move soon or undertake major renovations; owners of existing smart controls (e.g. Hive or Nest); and households with infants, elderly people, or anyone suffering from a heat-related health condition. This was to reduce the chances they might leave during the study or want to remove the system whilst renovating; to involve mainstream consumers rather than early adopters of smart energy technologies; and reduce the risk that any technical problems with the heating controls might harm the occupants. In this way, the Living Lab homes are not fully representative of a national sample but do reflect a broad mix of housing types and household compositions with a very broad range of occupancy patterns, income, and energy consumption patterns.

3.3 Data collection, sampling and analysis

All participants were provided with zonal heating controls that they could control from smart phones or any web browser. It thus involved the installation of an array of smart heating components into every home (See Figure 1), including:

- A “hub” which operates on its own internal wireless network, or z-wave;
- Wireless radiator valves;
- Individual room humidity sensors;
- Individual room temperature sensors;
- Individual radiator sensors;
- Central boiler controller;
- Utility flow meters;
- Water pipe sensors;
- Repeater to boost the signal from the hub to devices around the home;
- Batteries.

Participants also took part in a range of consumer research studies and had their homes were surveyed.

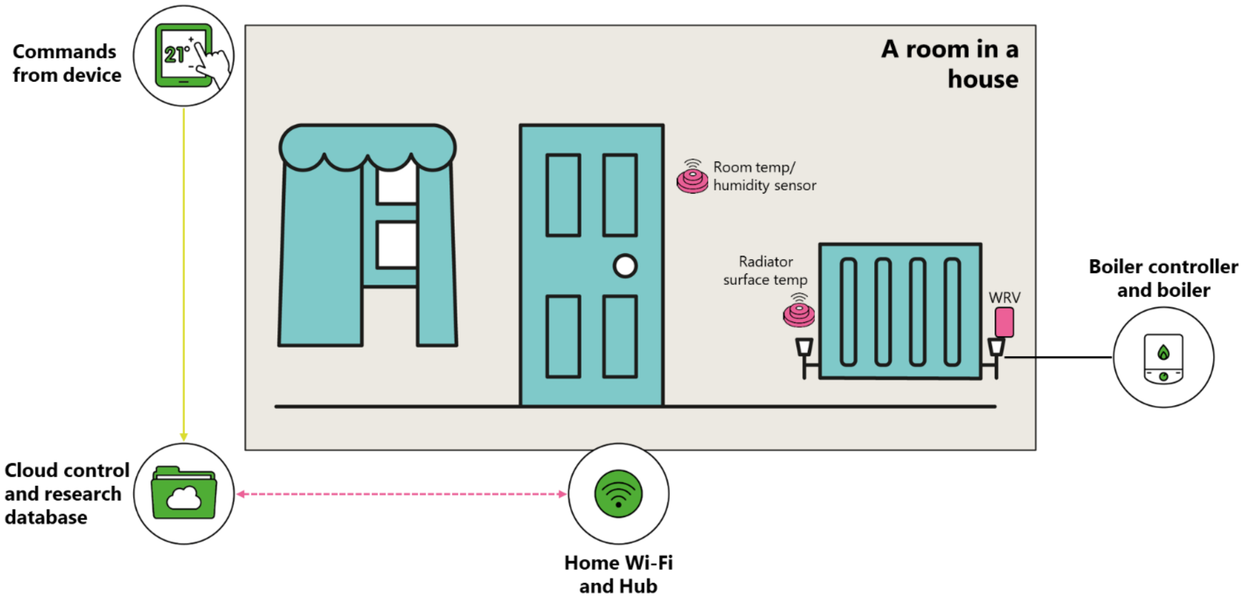


Figure 1: Heat controls, applications, and scheduling available in the Living Lab

Source: Authors, based on Living Laboratory data.

To complement the quantitative data collection, a mix of qualitative techniques were also implemented, and which are used primarily in this study. As Figure 2 reveals, these included research visits complemented by an extensive array of repeated data collection instruments such as:

- A pre-installation interview;
- Undirected diary studies and blogging, done in written and video forms;
- Directed diary studies and blogging, done in written and video forms;
- Repeated satisfaction surveys;
- Annual discernment surveys (used to understand how discerning Living Lab participants were in terms of the heat experiences they valued).
- One market segmentation survey;
- Interactive interviews (sharing screens and data);
- Heat Plan "Demos" or workshops run to show participants how their smart heating systems worked, how to plan their heating, what theirs would cost and to answer their questions;
- Semi-structured household interviews.

A researcher also visited every home participating in the Lab at least three times a year. Homes were recruited primarily by telephone before they were booked in for a home survey to ensure their home is compatible with having the controls fitted. The demographics of the 100 Living Lab homes are shown in Table 2.

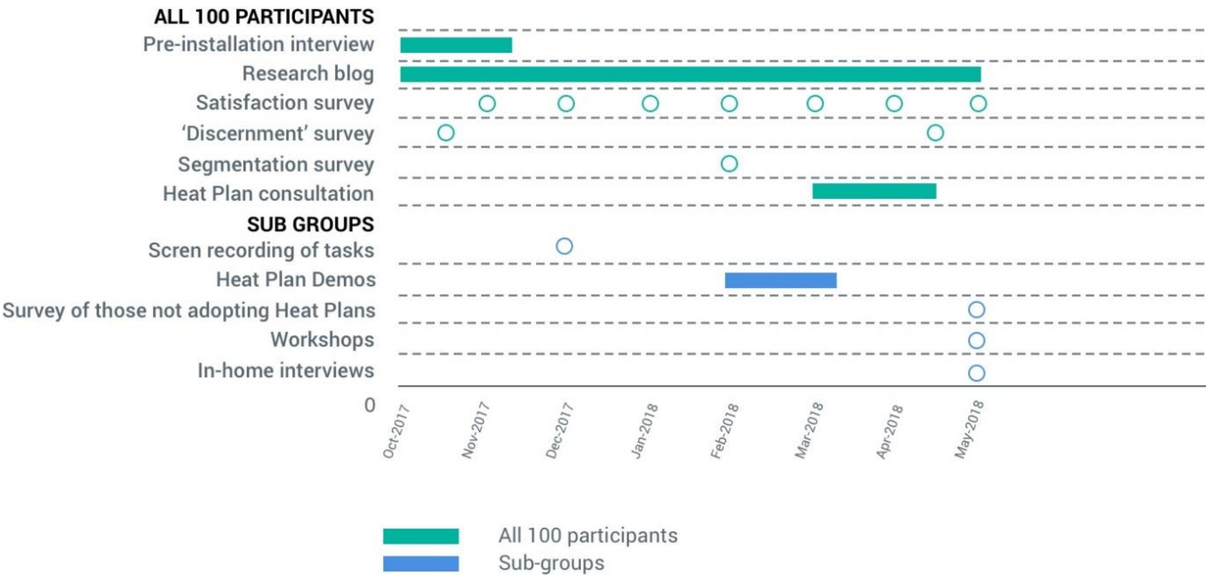


Figure 2: Overview of consumer research in the Living Laboratory, 2017-2018

Source: Authors, based on Living Laboratory data.

Table 1: Composition and demographics of the 100 homes in the Energy Systems Catapult Living Lab

a. Geographic composition

West Midlands	Manchester	Bridgend	Newcastle
26	5	32	37

b. Demographics of households

Age of lead participant

- 18-34: 8%
- 35-44: 30%
- 45-54: 31%
- 55-74: 28%
- Unknown: 3%

Household type

- Family with adult children: 10%
- Family with children: 50%
- Cohabiting couple: 24%
- Adults cohabitating: 2%
- Single adult: 11%
- Mixed generations: 3%

Types of Homes	**Age of Homes**	**No. of Bedrooms**
Bungalow: 3%	Pre-1945: 38%	1 bedroom: 1%
Mid-terrace: 13%	1945-1980: 33%	2 bedrooms: 16%
End-terrace: 5%	Post 1980: 26%	3 bedrooms: 46%
Semi-detached: 52%	Unknown: 3%	4 bedrooms: 28%
Detached: 24%		5 bedrooms: 9%
Ground floor flat: 2%		
Unknown: 1%		

For this particular paper, three sets of primary qualitative data from the Living Laboratory were utilized to document the lived experiences of heat: (1) telephone household interviews (N=100 in pre-installation call and N=42 in a tailored heating option call), (2) household diaries (N=75), and (3) at-home in person household interviews (N=30).

First, *telephone interviews* were carried out during the pre-installation phase of the controls and for reviewing heating service designs. These telephone interviews provided participants with the opportunity to raise concerns or share their questions and experiences with the researchers. These interviews lasted approximately 60 minutes, with all homes involved in a pre-installation call and 42 participants taking part in a call reviewing tailored options of a heating service.

Second, online *diaries* were used to record household experiences of having the controls in their homes and their interactions when heating their home. Indeemo, a mobile ethnography app, was used manage these online household diaries. Although this option was offered to all households, exactly three-quarters (75) chose to utilize them during the Living Lab.

Third, *at-home interviews* were conducted with a sub-sample of Living Lab participants to provide a deeper understanding into participant perceptions of smart heating. Almost a third of homes (30 participants) each took part in a 90-minute home interview. These interviews were used to understand the captured sensor data relating to the temperatures, spaces and times participants heated their home.

All interviews and diaries were recorded and fully transcribed. The research team repeatedly searched the transcripts of the interviews and diaries, developing a qualitative inventory about their experiences with smart heating controls. More specifically, the data for this paper were collected from just under 1700 blog posts, 26 home interview transcripts (made up of approximately 10000 - 15000 words each), and 42 consultation call transcripts (ranging from approximately 4000 - 8000 words each). The team searched this inventory for common themes concerning temperature preferences, heating practices, control of heat, and possible heating conflicts.

3.4 Limitations

Although we stand by the study's results, our approach does possess limitations. The 100 Living Lab homes are not representative of the UK, as the study did not include homes in social housing blocks, or non-homes such as apartments or rented rooms. Further, the ESC is bound by strict ethics and confidentiality agreements that err on the side of protecting the privacy of participating homes. Therefore, we are unable to offer interview schedules and topic guides due to ethics and approval constraints at the ESC. Lastly, we fully acknowledge that many of our findings may not be necessarily exploratory, but are instead confirmatory, supporting findings from earlier studies of the variation in heating practices and preferences (e.g. Dimitrokali et al. 2015; Eon et al. 2017; Kane et al. 2015; Miu et al. 2019), a fact that we believe still has value for its ability to triangulate earlier research.

4. Results: Temperature, Time, and Space in Smart Heating

This section of the paper presents our results through the lenses of three key aspects of households' home heating preferences: temperature, time, and space. These were revealed by combining data about how they used their zonal heating controls (see Figure 3) and also how they explained their choices in the various pieces of consumer research.

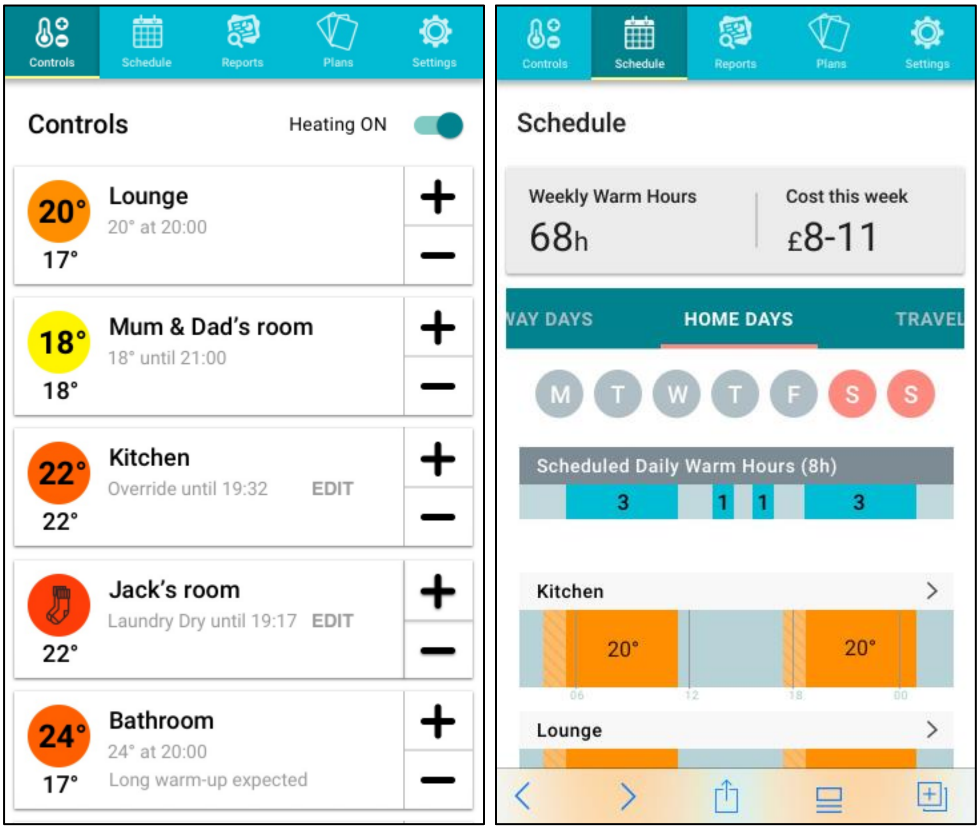


Figure 3: The interface Living Lab participants could use to control their heating

Source: Authors, based on Living Lab data. Living Lab participants could set the temperature in each room using their controls (left) and schedule when they wanted each room warm (right). The schedule showed how much their heating was predicted to cost in the following week.

4.1 Temperature preferences and tradeoffs between comfort, cost and values

Drawing from the extensive qualitative data collected Living Lab participants held very different preferences that could be summarized as either prioritizing comfort, cost, or value. These three rationales were categorized based on a number of criteria demonstrated in interviews and segmentation responses. Comfort focused households discussed valuing the enhanced control they received and the extra reassurance they could stay comfortable. Comfort was therefore a significant feature emphasized by households, with one even saying:

> *The house has never been so warm… I've noticed a massive difference in the house. It's probably costing us an absolute fortune, because now, you know, when I feel it's nice and warm, it's nice to keep it that way. You know, that's where you've got to pay if you're comfortable.*

Cost focused households were most likely to have switched suppliers, knew more about what they were currently spending and tried to use less heating so that they could save money. As one household put it:

> *Yes, we probably say, like, if I've got money to spend, the last thing I want to spend it on is gas, do you know what I mean? So, me and my husband would rather pay for a holiday, you know, so as much as we can, we'll switch it off. We will make do without it on, does that make sense?*

Value focused households liked knowing how much heating they were using and what they were paying, though they did not necessarily try to minimize what they spent, and instead valued things like cleanliness or sustainability. These different motives explain why participants with similar occupancy patterns can make different decisions. Some choose to heat the home before they get back so it is warm when they get in, others wait in the cold for it to warm up.

Tellingly, interviews with these households revealed the tensions and trade-offs between these three priorities of comfort, value and cost. Participants found it particularly hard to value their comfort, partly because they struggled to understand how much it cost to heat their homes in different ways. Indeed, most assumed they were paying a fixed price for their heating because they were charged a fixed amount monthly by direct debit. They only realized that it cost more to heat their homes when the weather was cold through discussion and the provision of the cost information on the user interface of their controls (Figure 3).

These heating priorities, and preferences, crystalized over time into six distinct heating patterns of use, grouped together based on temperature profiles and further defined by trends driving this behavior. These patterns—which we treated as mutually exclusive, meaning a household had to select only the single group that best described them—are outlined in Figure 4, with labels created by the authors but also validated with the households (i.e., they each identified with one of the distinct profiles during our follow-up interviews and data collection). "Cool Conservers" never heat their homes above 20^{o}C, and actively focus on keeping cooler temperatures. "Hot & Cold Fluctuators' have a less predictable schedule, and adjust heat all the time, or have lifestyles (e.g. children, shift working) that require flexible heating patterns. "On-Demand Sizzlers" represent the other end of the continuum than Cool Conservers, and always like it warm at 23^{o}C, sometimes as high as 26 ^{o}C, and never going below 20^{o}C. In contrast, 'Steady and Savvy' households rarely adjust settings, usually doing so only seasonally. "On-off Switchers" varied their target temperature the least, just switching heat on and off (usually in the winter vs. summer). "Toasty Cruisers" prefer heat not quite as hot as the sizzlers, but want constant warmth. Most interestingly, across the profiles, most homes request between 4-7 temperatures across their home, though a few homes requested only 1-2 different temperatures. Moreover, no single heating profile dominates the sample, with the top two, On-off Switchers reflecting only 28% of homes and Steady and Savvy reflecting only 24% of households.

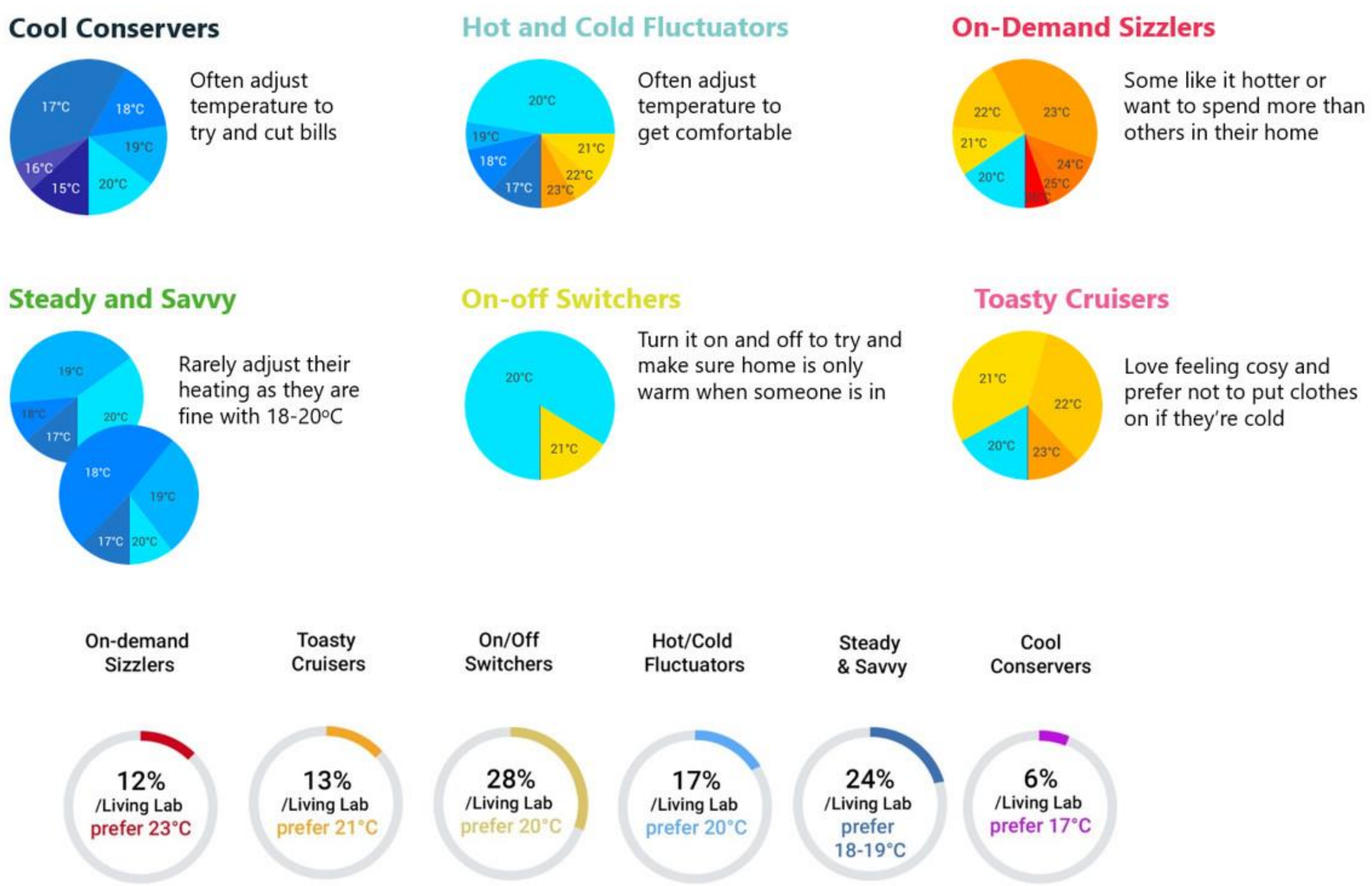


Figure 4: Six heating patterns and profiles with the preferred temperature for smart homes in the Living Laboratory

Source: Authors, based on Living Laboratory data.

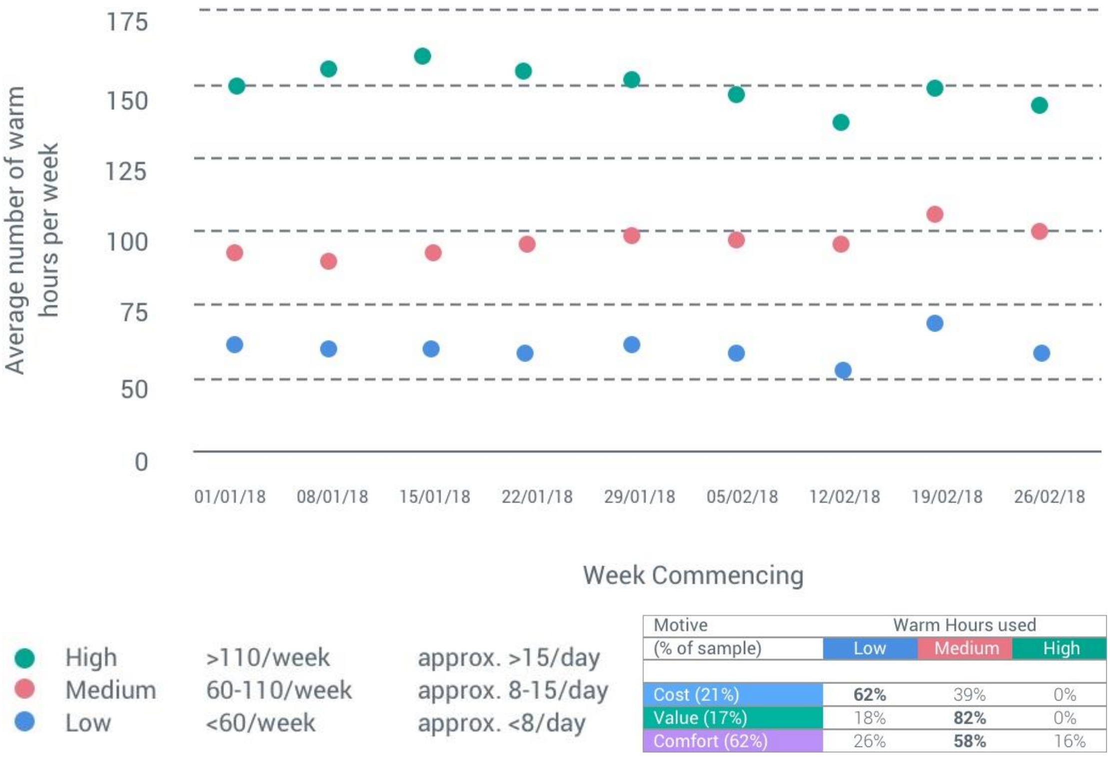
4.2 Time and the temporality of heating practices

A second core finding relates to time, or the temporality of heating, with people wanting different numbers of “warm hours” in their homes at very different times. Warm hours were defined as an hour when any room was warmed, so there were 0-24 per day. Participants could see how many warm hours they had scheduled each week (Figure 3). Interestingly, across the entire Living Laboratory, the Energy Systems Catapult found no correlation between the number of occupants and the percentage of rooms heated (Kendall's rank correlation tau 0.05269482 z = 0.54848, p-value = 0.5834).

Participants were classified as using high (>110), medium (60-110), or a low (<60) number of warm hours each week (see Figure 5a). There appeared to be a loose relationship between these groups and participants broader priorities. Cost-focused were more likely to use fewer warm hours, comfort-focused to use more and value-focused to use an intermediate number. Some households used a very similar number of warm hours each week (Figure 5b) whereas others varied significantly from week to week (Figure 5c). This variation was often caused by changes in how much time the home was occupied each week. Thus, the proportion of time spent at home at each temperature is temporally complex and dynamic.

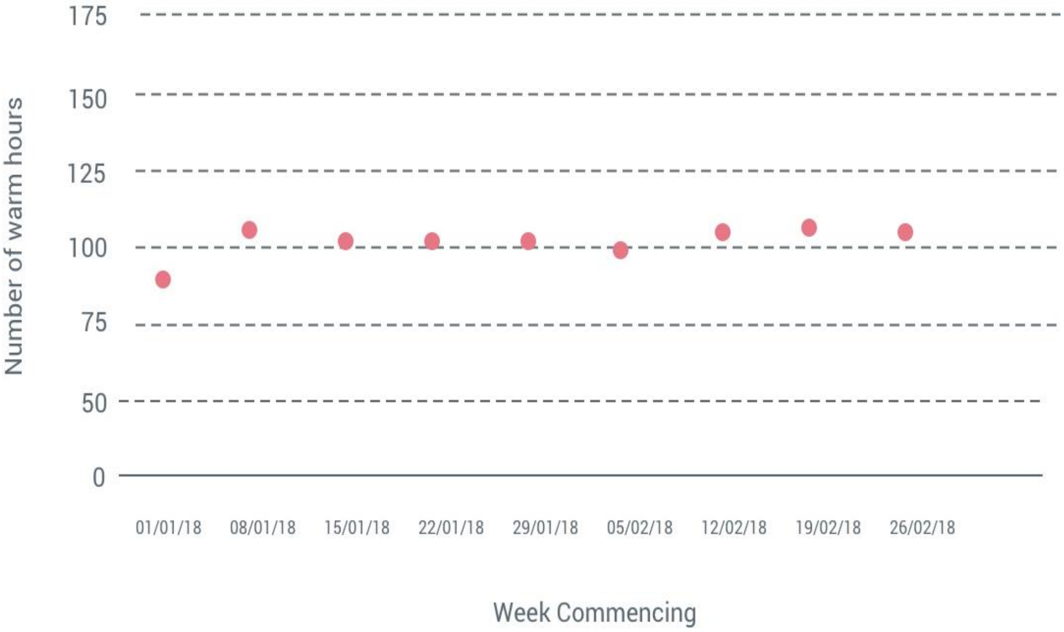
Moreover, some households, such as the “Steady and Savvy” and “Toasty Cruiser” household profiles shown in Figure 5 adjusted their heating less frequently and were much more consistent over time. Others such as the “On Demand Sizzlers” showed far more variation in the number of hours they used each. This variation was often caused by changes in the how much time their home was occupied each week.

A.



Motive	Warm Hours used		
(% of sample)	Low	Medium	High
Cost (21%)	**62%**	39%	0%
Value (17%)	18%	**82%**	0%
Comfort (62%)	26%	**58%**	16%

B.



C.

Figure 5: Variation in the number of warm hours used by different participants in the Living Laboratory

Source: Authors, based on Living Laboratory data. Panel A depicts the average number of warm hours per week across all 100 homes in the Living Laboratory for 9 weeks in January and February 2018. Panel B shows the heating profile for a household (with 4 people) that used a similar number of warm hours each week. Panel C shows the heating profile for a household (with 3 people) that varied considerably in how many warm hours they used each week.

4.3 Space and the extended control of heat

A third core finding is that households chose to heat different numbers of rooms. Participants were classified into three groups according to the proportion of their homes that they heated at any one time (See Figure 6). The "High" group heated between 60% and 70% of the rooms in their home (15% of participants). The "Medium" group heated just over 40% of the rooms in their home (41% of participants). The "Low" group heated around 30% of the rooms in their home (44% of participants).

Participants were able to turn heat down in rooms before the trial because they had thermostatic radiator valves (TRVs). However, most said that they did not adjust them very often because it took too much time and meant they might find a room cold when they wanted it to be warm. This is consistent with previous quantitative research which found that only 15% reported turning TRVs down to in rarely or unused rooms (Lipson, 2015), or that zonal controls are not always put to use even when they are available within homes (Beizaee et al., 2015, 2016; ESC, 2019).

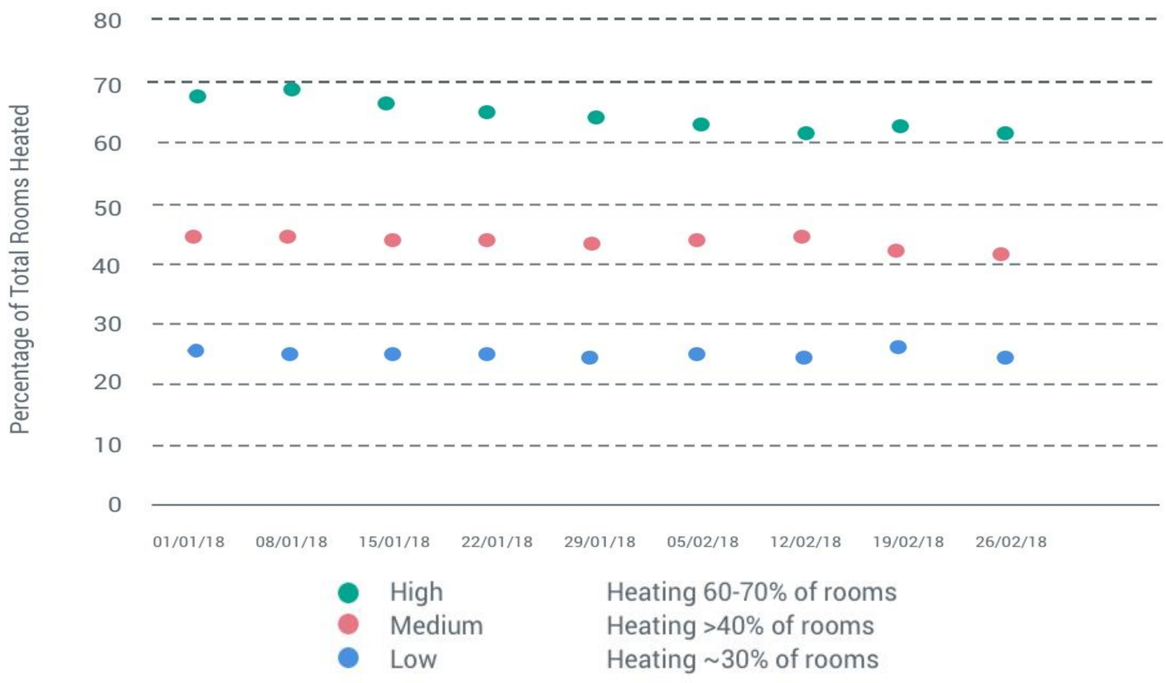


Figure 6: Percentage of total rooms "controlled" or heated in the Living Laboratory

Source: Authors, based on Living Laboratory data. The image depicts the average number of warm hours per week across all 100 homes in the Living Laboratory for 9 weeks in January and February 2018

Participants' stated motives helped explain why they were in each group. Those in the Low group were likely to be more concerned about the cost of their heating. They actively tried to conserve energy by only heating rooms when they were being used. By contrast, those in the High group were more focused on being comfortable and were more likely to keep more of their homes warm.

As such, our data suggests that people use this control to get different things. Some want more convenience or comfort. Others cut waste, or save money. One household for instance said that "*we still love the new system, much better than a manual system and seems to save us money*." Congruent with the notion that households value different attributes of smart heating, households used their new-found control in different ways, including temperature, total number of hours of warmth, rooms they heated, and how much flexibility they wanted. This reflected different preferences in terms of what they enjoy and how much they want to spend or use.

4.4 Beyond time, temperature and space

Furthermore, the Living Lab revealed other aspects of heat that participants wanted control of. Namely this included being able to make a radiator surface hot to get comfortable from radiant heat, not just air temperature, for instance by sitting up against it. It included being able to use radiators to dry clothing. It included being able to prevent heating waking participants up, either because of the noise of water flowing through pipes, or from temperatures rising in a room. Clearly there is more to households' experiences of heat at home than time, temperature and space.

Another indication of the desirability or undesirability of control relates to how participants used their controls. The data revealed huge variance in the level of active control people wanted. Some of the participants hardly touched their controls while others used them multiple times a day. Some people preferred to plan by adjusting their schedule, whereas others preferred to react and adjust the temperature of a room in the moment.

5. Discussion: Variation, temperature, retrofits and future preferences

Giving people more advanced control of their heating revealed important things about what they wanted. Their usage showed that they had very diverse preferences and wanted control of far more than the air temperature. Many struggled to get the experiences they wanted from their heating systems. This information could be used to improve the design of low carbon heating systems and to increase the appeal of home improvements that also improve building energy efficiency.

5.1 The implications of variation

Thermal scientists have long understood that a very broad set of physiological and psychological factors influence thermal comfort (Nicol et al., 2012; Brager and de Dear, 1998) and that people vary widely in their thermal sensitivity (Jacquot et al., 2014). However, most of these studies have been done in controlled laboratory conditions. Very few studies using real-life smart heating controls have explored what environments people actually prefer in their homes or why.

Giving households smarter controls revealed that they preferred to heat different parts of their homes to different temperatures at different times. Only some of this variation was caused by individuals finding different temperatures comfortable. It was also driven by differences in their lives – such as when they were home and how they used different rooms – and how much time, effort and money they were willing to spend getting comfortable. One household commented that:

> *The ability to control individual rooms is fantastic - I like my living areas warm but my bedrooms cool.*

Another extensive body of literature has focused on opening the black box of energy feedback; mainly whether providing feedback on household energy consumption will encourage energy saving behavior, and to what extent (e.g. Darby 2006; Gans et al. 2013; Martiskainen, 2007; Hargreaves 2018). However, Hargreaves (2018) for example has argued that instead of focusing on the effectiveness of energy feedback in delivering a certain amount of energy savings, we ought to first consider *what* feedback is provided and *on* what, and how this may link to other household and social practices. Van der Horst and Staddon (2018:1785), furthermore, highlight energy know-how, which is “considered important in both the monitoring of and management of energy consumption, involving comprehension, choices and behaviors”.

Our findings suggest that households would value better feedback on the cost of using their heating in different ways. Some of our participants spent time and effort trying to adjust their heating to use less energy, either to save money or reduce associated carbon emissions. However, they found it exceptionally difficult to find out how much energy was associated with the choices they could make. This is not surprising, as it is highly complex to understand the thermal dynamics of buildings. For instance, turning heating down in a rarely used room can save less energy than was previously used to heat it as heat still flows in from neighboring spaces (Lipson, 2015). Furthermore, the cost of heating varies with the weather: it takes more energy to warm rooms up on colder days.

Of course smarter heating controls have the potential to give consumers a much better understanding of the cost of heating their home in different ways. This could thus potentially aid in encouraging learning processes in relation to creating better energy know-how, while also enabling new imaginaries (e.g. Hargreaves 2018) to emerge so households can better consider how they may use heat to meet their needs in future.

It is tempting to assume that if consumers only knew what it cost them to heat their homes, they would all choose to adjust their settings so that they can spend less. However, this underestimates how much some people value their time and comfort. Our interviews with participants found some preferred to save time and effort adjusting their controls even if they paid for this convenience through using more energy. Others spent much more time adjusting their controls either to get more comfortable, or to try to save money. Some stopped worrying about heating a room for a little longer or to a slightly higher temperature when they discovered the sums involved. Others did try to save money by turning heat down when they went out. However, very few were prepared to sacrifice their comfort just to save money. More focused instead on getting the most out of the heating they bought, for instance trying to heat rooms when people were in them.

It may also be useful to think about the utility of feedback flowing in the other direction, from households to the designers of energy products, services and policies. In other parts of the private and public sectors, data is used to understand what consumers or citizens want to inform the provision of products and services. It is standard practice to assume households all want the same thing when calculating Energy Performance Certificates (EPCs), or boiler efficiency. This makes it harder to design policies that work well, and heating systems people want. Today consumers are accused of “taking back” energy savings from insulation (Sorrell 2007) and plumbers for installing “oversized” boilers (Wade *et al.*, 2016). Perhaps the real culprit is that inaccurate assumptions drive unrealistic expectations. It might be possible to use data from the emerging smart home to base these estimates on what people actually do instead.

The Living Lab enabled social scientists to overlay qualitative research with quantitative measures of how consumers controlled their heating and the temperatures they chose. This interdisciplinary approach provided robust evidence that when it comes to heating, as with every other aspect of human life from eye color to music taste, people vary. Energy products, services and policies will have more success if they are designed to deliver the range of experiences people want.

5.2 Beyond static air temperature set points to ambient and radiant heat

A great deal of attention is currently focused on static air temperature set points. Whether that is in models used to estimate energy performance in buildings (e.g. RdSAP), studies monitoring environments in real homes to update these assumptions (DECC, 2014), or recommendations for how we meet our carbon targets (CCC, 2019). Our findings suggest this focus may be misplaced. Instead, households seem to desire at least two different kinds of heat: ambient temperatures (or heat) at different points around their home; and radiant heat, achieved by making specific radiators hot, or achieving “bursts” of heat (see also Devine-Wright et al. 2014) .

The Living Lab showed that household heating practices can also evolve over time (see Figure 5b and 5c above). Participants gradually adjusted the temperatures they set for different rooms and the hours they scheduled their heating to suit their needs. Some households settled into a pattern faster than others. Those with unpredictable, irregular patterns of occupancy, for instance because they worked shifts or had visitors to stay, faced particular challenges. People with similar occupancy patterns can make different decisions. Some choose to heat the home before they got back so it's warm when they get in, others wait in the cold for it to warm up.

As with many smart controls the system had a "smart warm up" feature. Participants set the time they wanted rooms to reach a specific set point, the system decided when to turn the heating on to reach the set point. However, this meant they lost the ability to decide when the heating came on.

This presented problems for households who wanted to use their heating controls to make their radiators hot so they could dry laundry, or sit next to them and enjoy the feeling of radiant heat. This was so valuable to participants they complained that it was difficult to do. In these homes, our data also showed that households were making frequent increases to their requested temperatures in certain rooms to achieve radiant heat. Figure 7, for example, plots recurring statements or preferences about heat across the subsample of the 30 homes participating in at-home interviews. As a result, a feature was introduced so that they could use to make their radiator hot for a short "burst" of time, something we called a "heat burst."

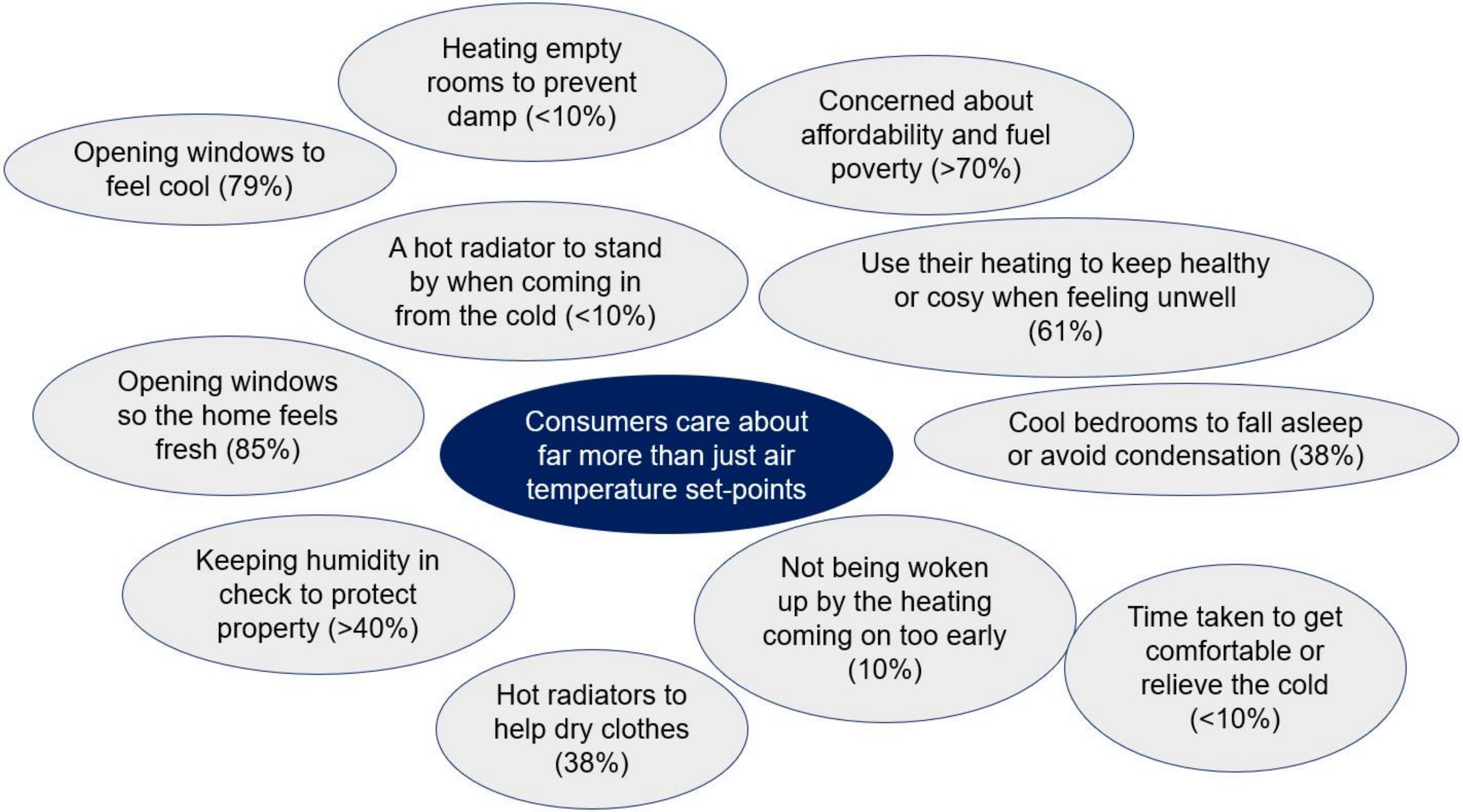


Figure 7: The complex dynamics of heating preferences (N=30 homes)

Source: Authors, inspired by Batterbee (2018)

Participants enjoyed the *convenience* of being able to make radiators hot when they wanted, rather than having to schedule their heating in advance:

> *Having to use heat burst quite a bit due to issues with the schedule, plus the wife has been home sick for the last fortnight.*

This convenience was considered particularly valuable when people felt they really needed heat, for instance to recover from an illness. Another household remarked:

> *Only good side of being ill, is that we have been able to manipulate the heat. So, we've been able to change the heat in order to help us recover from illnesses.*

Giving participants better control over their heating may enhance how discerning they are about what they like. They began to become aware that their thermal comfort depended on radiant heat as well as the air temperature. In the words of one household:

> *I thought the comfortable room temperature was the most important. With this system I found the room temperature could be at a level I used to feel comfortable, but I would still feel cold and only now I realize that it is because the radiators are cold.*

We also found that some participants preferred warmer internal temperatures on colder days. Here, a household remarked that:

> *Not sure if it's the icy weather spell and 6 feet of snow but I keep going in and amending it to higher to keep us warm.*

This may be because their walls were cooler and radiated less heat.

Another problem with "smart warm up" was that the heating system could wake up participants if it came on early to warm their bedrooms up to a set point. On colder days it would come on even earlier as rooms would need longer to warm up. Clearly, participants did not like being woken up. What was less expected was that they were also annoyed by the unpredictability of knowing when they would be woken. Once again, they wanted control of when their heating came on, not just the air temperature a room reached.

The Living Lab enabled researchers to discover that thermal experience is about more than time, temperature and space. Changing what aspects of their heating participants were able to control demonstrated that they cared about far more than air temperature set points. Once again, this has implications for designers of heating policies, products and services.

5.3 A new route to retrofits

The UK needs to improve the thermal efficiency of domestic buildings if it is to meet its climate change commitments (CCC, 2019). However, historic efforts to persuade people to invest in energy efficiency have struggled: there were only 13,860 “live” or “completed” Green Deal Plans in unique homes at the end of March 2019 (BEIS, 2019b). Evidence shows that 90% of renovations are performed to improve homes, not reduce what they cost to run (Wilson et al., 2013). This implies that consumers may be more open to increasing the energy efficiency of their homes if they can see how this would make them feel more comfortable.

Many participants put up with drafts, damp or overheating in their homes. As one explained:

> *I think we lose a lot of heat during the night through these doors. I mean, this room’s great in the daytime, because obviously it’s west-facing, so we get a lot of, you know, solar gain during the daytime, so actually it can almost get too warm during the summer months.*

The controls and sensor data revealed these problems were very widespread. This highlights that many households’ current heat experiences are likely to be sub-optimal.

There is potential to use this data to offer households tailored recommendations for how to improve their experiences of heat at home. For instance, it showed which participants were unable to get their rooms as warm as they wanted on cold nights. Some of these participants were asked if they would like to upgrade their home to solve their problem. Modelling showed that in some instances for instance, a larger radiator could improve comfort, reduce running costs and prepare a home for a heat pump in future (ESC, 2019).

The participants this was discussed with were quite open to the idea of their sensor data being used to make these sorts of tailored recommendation. As one household put it:

> *So, it’s interesting that you picked up that that one [a particular sensor reading], we do know that radiator needs changing. So yes, I think it would be good to have that [tailor recommendations] in built into your [heating] plan.*

Living Lab data on discomfort and building performance led to a more granular understanding of the prevalence of heating troubles in the UK. Previous surveys have suggested that around two-thirds of people report damp, drafts, condensation, overheating, even in winter (Lipson, 2015). The Living Lab sensor data showed problems may be even more widespread. In practically every home it was possible to identify these sorts of issue. It may be possible to use this data to motivate households to renovate their homes to solve these problems, improving the energy efficiency of their building at the same time.

5.4 User knowledge and future preferences

Retrofits that improve building efficiency can reduce energy demand. However, households will also have to upgrade their heating systems from using fossil fuels to low carbon alternatives. Despite the availability of various options, uptake has so far remained low: as of May 2019, there had only been 70,000 applications for the renewable heat incentive since November 2011, fewer than 10,000 per year across the UK (BEIS, 2019b). This compares with industry estimates of more than 1.5 million gas boiler installations per year (Macdonald, 2019).

It is already well known within some of the literature of pro-environmental behavior and psychology that one of the strongest indicators of future low-carbon practices is experience or ownership of another existing low-carbon product. That is, for example adopters of electric vehicles (EVs) are more likely to consider adopting other innovations such as solar panels or to eat less meat (Ryghaug and Toftaker 2014).

Findings from the Living Lab add nuance and context to this literature. Participants were asked whether they might consider switching to an alternative, low carbon heating system when they replaced their gas boiler. Whilst open to the idea, and keen to behave in a more environmentally sustainable manner, they raised various concerns about how their bills might change and how well the new system would work: chiefly, would they be able to get the heat experiences they wanted for a price they could afford? They also asked about the appearance of any new system, how noisy it might be, how long it would last and how easy it would be to repair.

These types of concern are common when consumers face any unfamiliar new technology. They will need to be persuaded that the benefits outweigh the potential costs before they purchase. Other sectors have built in approaches to their sales strategies, like ‘try before you buy’, specifically to overcome this challenge and there is evidence it can increase uptake of low carbon technologies. For instance, studies have shown that experience test driving an EV in China (Sovacool et al. 2019) or the Nordic region (Sovacool et al. 2018) greatly increases the changes that the person will adopt or use an EV in the future.

Similarly, Living Lab participants stated that they would be much more open to switching to alternative, low carbon heating systems if they were sure they would get the heat they wanted for a price they were willing to pay. To investigate this, interviews with a subset of about half the sample (n=48 homes) explored the concept that participants could buy their heat as a service where they could pay a fixed price for the number of warm hours they wanted at the temperatures they liked. We found that participants were more open to low carbon heating, in our case a heat pump, when they were confident they could get the service outcomes they wanted for a price they were willing to pay.

It is worth noting that participants did not appear to become “greener” *per se*. Instead, this smart heat service addressed their concerns by giving them confidence they would be able to get comfortable for a predictable price. In total, 85% of these Living Lab participants said that they would be open to the idea of replacing their gas boiler with an alternative, low-carbon heating system if they were given a guarantee that their current levels of comfort and cost could be maintained. This compares with only 36% of households in our segmentation survey of a representative sample of 3,000 owner-occupiers with gas central heating in the wider population.

This shows how Living Lab relationships with households enabled a far more sophisticated investigation of new business models than is typically possible in standard qualitative research. The concept of energy as a service could be brought to life using data from specific households, rather than in a more abstract hypothetical manner as is more usual when testing innovation concepts. Participants could understand how a new service might work because they were familiar with the concept of “warm hours” from their scheduling their heating using their controls (Figure 3, right). They were also convinced by their experience living with smarter heating controls that it would be possible to deliver this sort of experience in the real world. The Living Lab enabled this new consumer proposition to be tested faster than launching it in the market.

6. Conclusion and Policy Implications

In sum, our Living Laboratory data from 100 homes spread across the United Kingdom, as well as supplemental surveys with the UK public and repeated household interviews, reveal that temperature preferences vary greatly within homes. Some homes prefer two temperature settings all year around (heating on, heating off), whereas others prefer as many as seven different temperature settings (using profiles we described as Hot & Cold Fluctuators, or On-demand Sizzlers). Temporality of heat, i.e. the number of hours different rooms are heated and the temperatures they are heated to, changes over time. This creates dynamic demand among households for smarter heating control.

The way consumers use their control also coevolves with their preferences, for instance about how much they value their thermal comfort. Our data demonstrates that using more advanced control can increase consumers' understanding of what types of heating experience they like. They may begin to distinguish between air temperature and radiant heat, or want control over new aspects of their heating, like when it comes on in different rooms. Smart controls can thus help households understand what heating experiences they like and reveal these preferences to those aiming to improve or decarbonize them. With this in mind, we offer three conclusions or policy implications for engineers and researchers designing heating systems; businesses and the private sector retailing energy; and local and national planners.

For engineers and researchers designing heating systems, our findings suggest that interfaces should be built to create a shared understanding between customers and industry. For example these include the following issues to consider: How heat choices in one room may limit choices available in another room due to heat flows. How system components, such as radiator size and location, may limit achievable service performance levels. What the optimal balance is between "scheduled" use, which is regular enough that it can be planned for, and "on-demand" use, which is less regular. What the reasons are for "on-demand" heat use, and whether we can distinguish between a need for higher air temperatures or radiant heat. What the cost for "on-demand" heat use is relative to "scheduled" use. This also includes considering evolving the mental model of control from time the heating system is switched on to the time an outcome is achieved, such as a space being warm or a radiator being hot to dry towels. Consumers will prefer devices that can meet their broad, complex and unpredictable, range of customer needs.

For energy retailers, our findings suggest that it may be possible to use digitalization to sell heat as a service. Other sectors (automotive, supermarkets and telecoms) have designed their products and services to reveal how much consumers value different aspects. Whereas energy focuses on getting consumers to switch to drive competition, these other sectors obsess about how to deliver more value. Clearly consumers do want very different types of experience, this highlights the value of developing something similar for the energy sector (Fell 2017; Sovacool et al. 2019b). Early offers may not appeal to all, but simple improvements and more experience may increase uptake. This creates many new commercial opportunities, for instance, service providers could offer consumers more value than merely supplying their energy (e.g. cost certainty, confident comfort and tailored home improvement advice). Businesses could apply sales, usage and performance data to design better heating solutions. Energy service providers could accelerate decarbonization of heat, for instance by increasing consumers' confidence that they will get the heat they want from low carbon systems, or by discovering who is best suited to which low carbon technologies and preparing those who are not. Other options that emerge include integrating components to tailor high quality, low carbon heating solutions for each household, and informing local energy strategies and investments in new networks (e.g. district heat, electricity). There is a strong business case for smart energy propositions including selling energy as a service. Business may find it easier to attract and retain customers if they can offer a range of propositions to meet consumers' varied demands for heating experiences.

For policymakers, our study shows how smart heating preferences and practices coevolve over time, with users coming to "learn" their own needs and shift behavior to meet them. Moreover, our data suggests promise in exploring the design of an outcome-based (technology-neutral) decarbonization obligation approach for incentivizing decarbonization policy, one that revolves around the themes of cost, comfort and values, as well as on-demand versus scheduled heat, and ambient versus radiant heat. Policies may need more strongly based around the divergent ways households put smart heating systems to use, ensuring not only that they go with the grain of behavior and needs, but also recognizing that smart heating controls can play a key role in how those needs are co-constructed. In other words, household needs and behaviors do not necessarily preexist the policies and controls in place for heating, existing as some sort of separate domain; instead, household behaviors and needs become co-constructed with the policies and controls that would seek to intervene in them to modulate their dynamics. Policies need to also consider which types of homes and consumers may be best-suited for particular low carbon technologies, and promote the emergence of new business propositions (e.g. energy as a service) that presents significant potential to enable the transition to low carbon heating solutions.

In the end, our study is yet another reminder, with a high degree of confirmation with other studies and triangulation across out qualitative data, that people care about being warm and comfortable at home, not necessarily which fuel is used. Research, technologies, business models and policies must collectively recognize that not everyone wants to minimize cost, and that consumers use heat in diverse and ever-varied ways.

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